PLANETARY ENTRY PROBES IN THE FORESEEABLE FUTURE: DESTINATIONS, OPPORTUNITIES, AND TECHNIQUES

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ABSTRACT

Planetary atmospheric entry probes fill an important niche in NASA's solar system exploration plans, and current plans indicate they will continue to do so in the foreseeable future. The recently released National Research Council document "New Frontiers in the Solar System: an Integrated Exploration Strategy" [1] and multiple NASA planning documents [3][4][5] include calls for future missions specifying entry probes as the technique of choice for achieving many high-priority science objectives. Other missions described in those and similar documents, whose primary science objectives do not require entry probes, could deliver and support entry probes without greatly altering their fundamental architectures. NASA has in place several programs by which such missions could be implemented, each open to non-US participation. Beyond these currently envisioned missions, new techniques can expand the range of potential destinations and operating conditions for entry probes, opening up new opportunities for entry probe science investigations. Missions described in the planning documents are summarized, example new techniques are described, and examples are given of mission destinations enabled by the new techniques.

1. INTRODUCTION

Measurements made from planetary atmospheric entry probes have contributed significantly to our knowledge of the atmospheres of Venus and Jupiter, and subsequently to our understanding of solar system formation. Spacecraft entering Mars' atmosphere and landing there have also contributed to understanding Mars and its atmosphere. Further scientific advances are expected from entry probe missions, as evidenced by the list of missions recommended in the recently released National Research Council document, "New Frontiers in the Solar System: an Integrated Exploration Strategy" [1], and in recent NASA strategic planning documents and roadmaps [3][4][5]. The recommended missions by no means exhaust the potential of entry probes: there are some recommended missions that currently do not include entry probes, but could, with relatively minor architectural changes; and new methods and techniques could expand the envelope of scientific investigations possible with entry probes. NASA has several mission implementation programs of varying scope under which entry probe missions could be flown, providing NASA and potential Principal Investigators (PIs) with options for matching mission scopes and complexities to programs.

In this paper I first summarize NASA implementation programs appropriate for entry probe missions. Next I list and summarize missions discussed in the NRC and NASA documents, then missions in those documents that could be easily augmented to carry entry probes. Finally, I briefly discuss example new methods and techniques, giving examples of new destinations or regions they make available for scientific investigation.

2. NASA FLIGHT MISSION IMPLEMENTATION PROGRAMS

NASA has in place various means for implementing space flight missions, including missions that deliver and support atmospheric entry probes. These means fall into two broad categories: NASA-managed, and "community-based."

2.1 NASA-Managed Missions

When NASA manages a mission it assumes full responsibility for the mission. Potential science PIs propose, in response to a NASA Announcement of Opportunity (AO), instruments and investigations for inclusion in the mission. Selected PIs work with NASA to establish the detailed mission design and science operating plan. NASA-managed planetary missions generally have large budgets appropriate for complex, challenging missions of broad science scope. NASA frequently encourages non-US participation in such "flagship" missions, negotiating such participation subject to approval from the US government. The Cassini mission to Saturn is an example of a NASA-managed mission with significant non-US participation. In addition to including non-US contributions on the Cassini orbiter, that mission operates in cooperation with the ESA Huygens mission being delivered to Saturn's moon Titan by the Cassini spacecraft.

2.2 Community-Based Missions

In community-based programs potential PIs propose, in response to a NASA AO, entire missions, including mission architecture and design, launch vehicle, science objectives, instrumentation, and investigations, spacecraft design and implementation strategy, and all other aspects of a complete space flight mission. A selected PI is responsible for the entire mission. Projects undertaken as part of a community-based program are cost-capped, and generally are simpler missions with more focused science objectives than NASA-managed flagship missions. Non-US participation is specifically encouraged, and is negotiated by the PI subject to approval by NASA and the US government. Some of these programs are capable of implementing entry probe missions and are discussed below. Due to the combination of the character of Mars' atmosphere and the relatively high maturity level of Mars exploration, Mars entry probes *per se* are not part of NASA's plans so are not covered in this and subsequent sections. But some instrumentation usually considered appropriate for entry probes can indeed ride along on Mars surface landers and yield useful atmospheric science results.

One of the first relatively large community-based programs, the Discovery Program has operated since late 1993 and has so far produced several innovative missions and significant science results. The last AO, released in 2000, was cost-capped at about $300 million US. The next AO, scheduled for release in 2004, is expected to raise that cap to about $350 million. NASA's intent is to release a Discovery AO every 18 to 24 months, but budget problems have delayed the AO now expected next year. Allowed science objectives broadly span solar system planetary science and even extend to extrasolar planetary systems. Potential destinations are almost anywhere in the solar system that the cost cap will allow.

The New Frontiers Program is the newest and largest of the community-based programs. Larger in scope than the Discovery Program, its first AO, released in October of 2003, specifies a cost cap of $700 million US. Although this could potentially treat a larger range of science objectives than the Discovery Program, for the foreseeable future each New Frontiers AO will restrict allowed destinations and science objectives to a set of pre-determined, high priority targets and objectives. The 2003 AO specifies the remaining four "mid-size" missions described in the SSE Decadal Survey (SSEDS) after the New Horizons Pluto/Kuiper Belt mission was grandfathered into the program. NASA plans to release a New Frontiers AO every 36 to 42 months. Unlike Discovery, New Frontiers does not prohibit using nuclear electric power systems, so it is more amenable to outer solar system destinations.

Begun in 1958 with the launch of NASA's Explorer 1 into orbit, the Explorer Program began competitively selecting missions in the 1970's. It now consists of two programs, both smaller than Discovery, since the effective discontinuation of the even smaller University Explorer Program. The larger of the existing Explorer programs, the Mid-Size Explorer Program (MIDEX), last released an AO in July of 2001, with a cost cap of $180 million US. This is probably sufficient for a very limited-scope entry probe mission to a nearby inner solar system destination, and most likely represents a lower limit for programs that could support a complete entry probe mission. However, Explorer Program missions are intended to support just three of NASA's Themes: Astronomical Search for Origins and Planetary Systems, Structure and Evolution of the Universe, and the Sun-Earth Connection. These organizations would be reticent to fund an atmospheric entry probe mission.

In addition to full mission proposals, the community-based programs allow proposals for "missions of opportunity." The PI proposes to participate in, or add to the scope of, an existing mission by adding an instrument, investigation, sub-spacecraft, etc. It might be possible to add a simple entry probe to an existing mission via this route, but in a given program the cost cap for missions of opportunity is typically much less than (about a tenth of) that for full mission proposals.

3. RECOMMENDED MISSIONS INVOLVING ENTRY PROBES

I list here missions described in the NRC and NASA documents that specifically call for deep atmospheric entries. They are grouped by destination.

3.1 Venus

The 2003 SSEDS lists the Venus In-Situ Explorer (VISE) mission as a high-priority, near-term (before 2013) candidate for the New Frontiers program. This mission's science objectives include obtaining a documented sample of Venus surface materials, with *in situ* composition measurements from the sample location and detailed compositional and mineralogical analyses of the sample. Atmospheric composition and structure measurements are made during descent to the surface, and also during ascent to an altitude where conditions allow the craft to survive for a time needed for the rather lengthy sample analyses. The mission profile calls for direct entry on approach to Venus and descent to the surface. In the one to a few hours the craft spends on the surface it completes documenting the site with images and *in situ* compositional measurements, acquires the sample, and transfers it to a gondola. A balloon then lofts the gondola above Venus' sulfuric acid clouds, where temperatures and pressures are more

Earthlike (at the surface temperatures are more than 700 K and pressures are more than 90 bars), for the detailed sample analyses and data relay. The VISE mission is one of the four mission categories specified in the New Frontiers AO released in October of 2003.

In a longer-term time frame (after 2013) the SSEDS and the SSE Roadmap recommend the Venus Sample Return (VSR) mission, a very challenging mission in the flagship category. As the name implies, its prime objective is to return samples of Venus surface materials to Earth, where the full power of large ground-based laboratories can be brought to bear on them. Any sample return from a planetary surface is challenging, essentially requiring the landing of a sample acquisition system and an interplanetary space flight mission system on the surface of another planet. But the VSR mission is even more difficult than a Mars sample return due to the extreme conditions at Venus' surface, and the large mass of atmosphere overhead. As in the VISE mission, the high temperatures limit time spent on the surface. Returning to orbit from the surface may require ascending via balloon to reduce drag from the atmosphere. All this indicates a large mass to be landed on Venus' surface, and this will be a challenge for atmospheric entry and descent systems.

3.2 The Jupiter System

A polar orbiter at Jupiter is a nearly universal theme in current space science planning. The SSEDS and the Sun-Earth Connection Theme's Decadal Survey (SECDS) [2] both give such a mission high priority for the 2003-2013 decade. The SSEDS' Jupiter Polar Orbiter with Probes (JPOP) mission, a candidate for the New Frontiers Program, calls for multiple Jupiter atmospheric entry probes in conjunction with its polar-orbiter. It appears that the SEC Theme's mission (called "Jupiter Polar Mission" in [2], "Jupiter Polar Orbiter" in [6]) could be merged with JPOP without serious compromise of either mission's science objectives. The SSEDS description of JPOP probe science objectives calls for penetration to at least the 100-bar level at multiple latitudes within 30 degrees of Jupiter's equator, making measurements of composition (particularly water), temperature, wind, clouds, and sunlight as a function of pressure level. Delivery of multiple entry probes by the orbiter appears not particularly difficult, but challenges exist in two other critical areas: surviving entry into Jupiter's atmosphere at relative speeds between 47 and 60 km/s, and relaying data from the probes to the orbiter through Jupiter's radio-absorbing atmosphere, while planetary rotation and motion of the orbiter change the transmission direction significantly during the descent. JPOP is another of the four mission categories specified in the New Frontiers AO released in October of 2003.

3.3 The Saturn System

Saturn's moon Titan, with an environment rich in simple to moderately complex organic compounds, is the subject of intense interest in the planetary science community. Most scientists expect that soon after results from the Cassini and Huygens missions begin to appear in the literature, there will be a resounding call for a follow-on mission focused on Titan and its organic environment. The SSEDS and SSE Roadmap both give high priority to the Titan Explorer flagship mission, in the long term for the former and "mid- to far-term" for the latter, the more recent of the two documents. Mission profiles call for an aerocaptured Titan orbiter and an entry vehicle that delivers some sort of mobile science platform, preferably an "aerobot" capable of powered flight instead of merely drifting with winds. As currently conceived the aerobot would perform local mapping and detailed analyses of Titan's surface morphology, composition (with emphasis on the organic components), and the distribution of the constituents; study weather in the lower 10 km of the atmosphere, and surface-atmosphere interactions; and examine sources of energy driving the observed processes. The orbiter would use remote sensing instruments and radio occultations to study atmospheric composition, structure, and dynamics, and would perform global radar and IR mapping of the surface in an effort to extrapolate the aerobot's findings globally, and to understand Titan's global and regional geology. It might also serve to relay aerobot data to Earth. A recent study (completed September 2002) by NASA's Aerocapture Systems Analysis Team found that aerocapture of such a mission at Titan could be implemented with a fairly low-tech, low-performance aeroshell system, suggesting that a project start might be feasible well before the SSEDS's long-term time frame of 2013 or later.

3.4 The Neptune System

After the Voyager 2 flybys of the 1980's, the planetary science community has almost universally recognized the need to return to an ice giant planet for thorough exploration. The Neptune system offers both the ice giant and another high-priority object: Triton, which might be a captured Kuiper Belt object. Like a Jupiter polar orbiter mission, an orbital mission to the Neptune system is common to the SSE and SEC Roadmaps and the SSEDS, and could likely be implemented as a single mission. The SSE mission, "Neptune Orbiter with Probes," specifies also multiple entry probes into Neptune's atmosphere, for measuring vertical profiles of composition (particularly water, though entry probes may not penetrate deeply enough at Neptune to sample its interior abundance) and other quantities of interest in a deep atmosphere. Although survival of entry probes into Neptune's atmosphere is not as challenging as for

Jupiter, other aspects of the mission may present entry survival challenges. NASA recommendations about the duration of outer solar system missions suggest that a mission to Neptune should not spend more than 12 years from launch to Neptune arrival. This is much less than the approx. 31 years required for a quasi-Hohmann transfer from earth to Neptune, so the craft arrives at Neptune with a sizeable hyperbolic excess velocity. This increases the ΔV required for orbit insertion from about 1 km/s, easily implemented with a chemical propulsion system of reasonable mass, to more than 5 km/s, which would require that a great majority of the approach mass be propulsion system and propellant. Two identified means of handling this problem are Nuclear Electric Propulsion (NEP), and aerocapture. NASA's Aerocapture Systems Analysis Team recently completed a year-long study of an aerocaptured Neptune orbital mission that delivers entry probes. Results from that study should be announced at scientific and engineering conferences, and in journal publications, over the coming year.

4. RECOMMENDED MISSIONS THAT COULD BE MODIFIED TO CARRY ENTRY PROBES

Some of the missions recommended in the NRC and NASA planning documents do not call for entry probes but have orbits or other characteristics that lend them to delivering and supporting an entry probe, without unduly compromising the original science objectives. I discuss these below, and give examples of modifications that would allow them to include an entry probe.

4.1 Venus

The SECDS and SEC Roadmap documents describe the Venus Aeronomy Probe (VAP) mission as a high-priority, moderate-sized mission ($250-400 million US). Its near-polar orbit, 150 by 12 000 km with a near-equatorial periapse, skims Venus' upper atmosphere to observe *in situ* various processes and phenomena of the ionosphere and upper neutral atmosphere. The approach orbit could be altered easily to deliver an atmospheric entry probe. After releasing the entry probe, a maneuver of relatively small magnitude would place the VAP spacecraft on its intended approach trajectory to carry out its mission. Venus' relative nearness to Earth allows direct transmission of data to Earth, so VAP would not be required to handle data relay. The SECDS also describes this mission as "Deferred," because the concept is "Not supported by existing SEC mission lines." Making this a multi-disciplinary mission by adding entry probe science objectives might open new avenues for implementation.

Whereas adding an entry probe to the VAP mission might improve its advocacy base, another approach might achieve improved advocacy by turning the tables: have the VAP spacecraft piggyback on an atmospheric entry mission. Candidate carrier missions would include the VISE and VSR missions (See Section 3.1).

4.2 The Jupiter System

Both the SSEDS and SECDS, and the SEC Roadmap, describe a mission that would perform multiple Io flybys while in jovian orbit. The SEC version, called "Io Electrodynamics," would operate in a 5.9 by 71 Rj equatorial jovian orbit that yields perijove flybys of Io. This orbit is similar to that of the Galileo Orbiter as it received the Galileo Probe data, except that the Galileo Orbiter perijove was near 4 Rj. The Io Electrodynamics (IE) spacecraft could easily deliver a Jupiter entry probe, releasing it a few months before first perijove and then performing a maneuver to attain the desired perijove and timing for probe data relay and orbit insertion. The near-Jupiter orbit geometry is illustrated (at a notional level) in Fig. 1, showing the IE orbiter overflight of the probe entry site. Better data relay could be attained by moving the IE orbiter's approach trajectory such that the first perijove more nearly matches that of the Galileo Orbiter, near 4 Rj. This decreases the size of the orbit insertion maneuver by nearly 300 m/s (though this is offset by the maneuver required at first apojove to raise perijove to 5.9 Rj for the rest of the mission), decreases the data relay range substantially, and more nearly matches the orbiter's angular rate to Jupiter's rotation rate, for a longer relay window. The decrease in relay range yields a potential increase in the data rate by a factor of up to 2.5, or a proportional decrease in the required transmitter power.

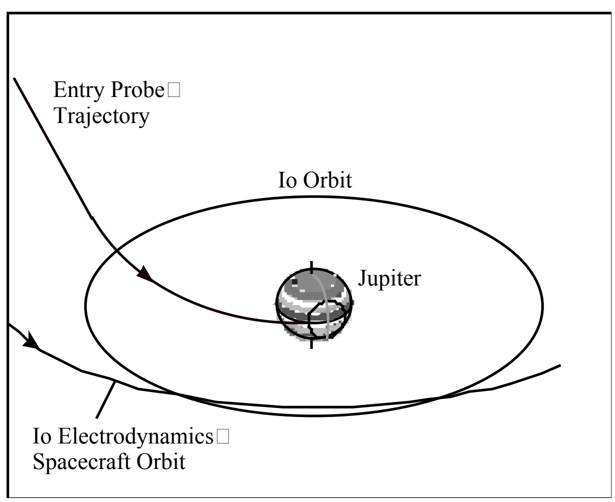

Fig. 1. Notional trajectories of the Io Electrodynamics spacecraft and a Jupiter entry probe it delivers and supports. Only the innermost part of IE's 5.9 x 71 Rj orbit is shown. Timing the probe entry such that the IE orbiter is overhead for data relay is relatively simple and uses modest amounts of propellant, if the relay is done during the first IE perijove pass.

The Jupiter system is scheduled by NASA to be the first visited by a new type of high-capability spacecraft. Slightly more than a year ago NASA announced an ambitious program, Project Prometheus, to make available for space science missions a suite of nuclear power and propulsion systems, including ion propulsion systems powered by nuclear fission generators. Plans call for the first mission to use this NEP technology to be the Jupiter Icy Moons Orbiter (JIMO). This mission targets Europa, Ganymede, and Callisto, the three outer Galilean satellites of Jupiter, spending time in close orbit at each. Much time is also spent transferring from one satellite to the next, and the project plans to spend at least part of that time observing Jupiter itself, so Jupiter science is part of the planned mission science. Studies indicate that there are ways by which JIMO could deliver and support a deep entry probe into the jovian atmosphere. One of the high-priority recommendations to come from the "JIMO Forum", held at the Lunar and Planetary Institute in June of 2003, was that the JIMO Project should consider the options available for adding an entry probe, given the high-priority science to be achieved. Unfortunately, just prior to the October 2003 workshop in Lisbon the JIMO Science Definition Team recommended against including an entry probe. That is most likely due to its large impact on the mass available for the primary science payload, and the large changes in the mission design (which delay arrival at the first satellite by several months) to accommodate data relay. This is not a final decision, but it does make including an entry probe on the JIMO mission fairly unlikely.

4.3 The Saturn System

Although not an entry probe mission *per se*, the Saturn Ring Observer (SRO) mission involves aerocapture in Saturn's equatorial atmosphere on the way to locations immediately adjacent to (just outside the plane of) Saturn's extensive ring system. *In situ* instrumentation that could be used during the aerocapture, such as a helium abundance detector, could contribute greatly to Saturn atmospheric science. The SRO spacecraft could also deliver a Saturn entry probe, releasing it upon approach a few months before aerocapture. But since SRO also involves an atmospheric entry on a trajectory not markedly different from that of the entry probe, the data relay task may be difficult. Probe delivery after aerocapture might help the relay problem, but has problems with the probe colliding with ring particles, unless the probe, at greatly increased cost, risk, and complexity, carries its own propulsion system. An NEP version of SRO that traversed the entire ring system could deliver a Saturn entry probe from a low near-circular Saturnian orbit, near the end of the mission. Such an entry probe mission could benefit from use of techniques discussed in the next section

5. NEW TECHNIQUES

An exhaustive listing of all proposed techniques applicable to atmospheric entry probes would fill a tome, and is not the intent here. In this section I first highlight two examples of techniques not yet used in atmospheric entry missions, discuss their benefits, and give examples of potential applications. Then I briefly mention a few more such techniques. Rather than provide a reference document, my purpose at the Lisbon workshop was to stimulate creative thinking by the attendees.

5.1 Multiple Linked Descent Modules

Past entry probe missions involved only one-piece probe systems. Some missions delivered multiple probes, but those probes did not communicate with each other. Missions such as the Galileo Probe have used a relay link strategy, but the relaying element was outside of the atmosphere. There are benefits to be had from deploying multiple, linked descent modules in a single mission, and these benefits directly address problems encountered in some high-priority probe missions.

Researchers proposing deep-penetration entry probe missions at planets such as the giant planets, whose very deep atmospheres contain radio-absorbing constituents, are universally confronted with two problems: 1) establishing a data relay rate sufficient to transfer the needed data to a relay spacecraft, and 2) covering a large altitude range within a data relay window imposed by orbital mechanics, with vertical resolution sufficient for the science investigations. The first problem stems from the compounding problems of atmospheric attenuation of the signal and large relay distances (typically hundreds of thousands of km). The second stems mostly from the large vertical distance to traverse, and somewhat from the behavior of aerodynamic decelerators such as parachutes in a real atmosphere. As a fixed mass descends under a fixed-geometry parachute, the descent speed slows as a result of the increasing atmospheric density with depth. Both problems can be addressed by using multiple descent modules.

Using a Jupiter deep probe as an example, the relay orbiter is typically some 2-300 000 km distant from the probe, and at L band frequencies (optimum for a Galileo-like relay at Jupiter) the vertical overhead opacity at the 100-bar level is approx. 10 dB (2.3 optical depths). At zenith angles up to about 60-70 degrees, where planetary curvature has little effect on path lengths, the opacity goes roughly as the inverse of the cosine of the zenith angle. A single probe at that depth, using a Galileo-like communications system, could relay some 30-40 bps to the orbiter directly overhead.

Consider instead a deep module communicating with the same transmitter to a shallower module at the 2-bar level some 250 km above and removed some 400 km horizontally due to wind shear, for a total relay range of about 500 km. Both modules must use nearly omni-directional low-gain antennas (LGAs) to accommodate the horizontal separations, so the deep probe loses about 10 dB of gain and the shallow probe loses about 20 dB compared to the orbiter's high-gain antenna (HGA), for a total loss of about 30 dB. But the relay range decreases from about 250 000 km to only 500 km, a divisor of 500, for a factor of 250 000 (54 dB) increase in signal strength, a net gain of 24 dB. This link could support nearly 10 kbps. From the shallow module to the orbiter, the distance is still about 250 000 km, but the overhead opacity is now less than 1 dB, and that link will support about 250 bps. The deep module could send about 125 bps to the shallow one (with a much reduced transmitter power!), while the shallow one generates 125 bps of data itself and relays both data sets to the orbiter. If, as in some recent studies, the transmitter power for the link to the orbiter is increased and/or the aperture of the orbiter's reception antenna is increased, higher data rates are possible.

This same scenario can address the traversal problem. Typical maximum relay window durations at Jupiter are about 1.5 hours, or about 6000 seconds. In that time a probe to the 100-bar level must sample a region about 320 km in vertical extent, for an average descent rate of more than 50 m/s. Atmospheric scientists usually express sampling requirements in terms of samples per scale height. Near the 100-bar level the scale height is large due to higher temperatures, and the density is high so the probe descent rate is slower than average; it is easy to acquire many, in fact too many, mass spectrometer samples in one scale height. At the half-bar level, the scale height is quite low due to low temperatures, and the density is also low so the probe descends much faster than average; it is difficult to acquire the needed number of samples per scale height. Increasing the parachute size achieves the sampling requirements at the shallow levels, but it slows the descent too much at the deeper levels so that the 100-bar level is not reached before the end of the relay window. Using the two-module technique, the system is designed such that the deep module traverses the 10-bar to the 100-bar levels at the same time the shallow module traverses the 1-bar to 10-bar levels, giving more, and more balanced, coverage to the intervals (these pressure levels are not the true optimal division of the interval, but are intended only for illustrating the concept).

Applications with more than two modules might sample very deeply into giant planet atmospheres, far below the 100-bar levels. This might be necessary to measure *in situ* atmospheric dynamics (winds) representative of the deep interior at all the giant planets, and also to measure the global abundance of water at the ice giant planets Uranus and Neptune. Sampling the global abundance of water at Saturn will likely require a two-module system.

5.2 Ballute Decelerators

To date entry probes have relied on rigid aeroshells as the prime deceleration and thermal protection systems. The aerodynamics of such aeroshells in a real planetary atmosphere, along with the difficulty of reliably entering an atmosphere at shallow entry angles, constrain the maximum altitude at which the aeroshell can be jettisoned, and thus the maximum altitude at which the probe's instruments can start measurements. At Jupiter this altitude is at or near the tropopause, so most of Jupiter's stratosphere is inaccessible to entry probe instruments that must be protected inside the aeroshell. Attempts to enter tenuous atmospheres at bodies such as Io or Triton with rigid aeroshells would have the probes still in the aero-heating phase upon impact on the surface. Clearly, the high ballistic coefficients characteristic of probes with rigid aeroshells limit the atmospheric range of accessibility.

For some time now there has been discussion of inflatable decelerators called "ballutes." The basic concept is to spread the aerodynamic forces, and hence the heating, over a surface area orders of magnitude larger than that of a rigid aeroshell, greatly reducing maximum temperatures. This decreased heating rate also occurs at the payload, which would need only a thin thermal blanket to protect exposed areas from entry heating. What is lacking so far is materials with good high-temperature characteristics (hundreds of degrees C, not thousands), flexibility to allow packaging and subsequent inflation, and sufficient strength-to-weight ratio to handle the stresses of the deceleration without requiring more mass than a rigid system. Materials research is continuing and progress is being made, especially for certain types of polymers, but so far they are not ready for flight tests.

When the materials become available, ballute decelerators will enable entry probe sampling of atmospheric regions currently inaccessible to the usual *in situ* probe instruments. Probes with very low ballistic coefficients experience a deceleration time profile similar to those of aeroshell decelerators. But the deceleration occurs much higher in the atmosphere, so instruments can start making measurements at much higher altitudes, well into the jovian stratosphere, for instance. Another new venue would be in the tenuous atmospheres, at Io, Triton, Pluto, and possibly Charon. Scientists and mission designers have envisioned landers at these worlds, but so far the deceleration to landing must be handled propulsively, contaminating the atmosphere on the way down, and at great expense in propellant mass. If ballutes of sufficiently low mass can be developed, aerodynamic deceleration can significantly decrease the required propellant load, and allow measurements on uncontaminated atmosphere during descent until rocket engines perform the final landing maneuver.

Very large ballutes might increase the maximum mass we can land on Mars. As payload mass increases, in general the ballistic coefficient increases: mass goes as linear dimensions cubed, while surface area goes as linear dimensions squared. In effect, the more massive the entry vehicle, the more "transparent" the atmosphere becomes, *i.e.* it is less effective in slowing the entry mass before impact on the surface. Any required deceleration not accomplished aerodynamically must be done propulsively, usually with significant propellant mass penalty. Adding more area to a rigid aeroshell, in an attempt to increase the aerodynamic deceleration, often carries as much or more mass penalty than propellant. Adding much more area with a low-mass ballute moves the onset of significant aerodynamic deceleration higher in the atmosphere, yielding sufficient aerodynamic deceleration to burden rocket engines only with the final landing maneuver. If the ballute mass is less than the propellant mass (and tankage, etc.) required if the ballute is not used, this provides a larger landed mass fraction.

5.3 Other Examples

Planetary entry probes have been a part of planetary exploration for decades, yet it can hardly be considered a mature field: there is enormous potential for improvement and expansion, including many methods and technologies already discussed in the literature but as yet untested. I briefly mention three examples here, but they are meant only as examples to stimulate creative thought.

Instead of using a parachute to dissipate all the gravitational potential energy in a descending probe as atmospheric turbulence, some of that energy could be converted to electrical or mechanical energy via a wind turbine and generator. Mechanical energy could operate refrigeration equipment for thermal control in high-temperature environments, while electrical energy has be many potential uses, including more powerful radio transmitters.

Phase-change materials for cooling have been demonstrated in flight already, but there are many variations on the concept. In an effort to slow external heating, very deep probes at the giant planets can devote much mass to the pressure vessels of sealed descent modules. Mass savings might be made using phase-change materials in a device much like an air conditioner's heat exchanger, to pre-cool gases entering a vented vessel that is much lighter than a pressure vessel. Other phase-change materials would absorb heat released by compression of gases already inside as the probe descends.

Science investigations also stand to gain from new techniques. For instance, Doppler Wind Experiments would profit from having multiple receiving stations for a probe's data relay signal, reducing the ambiguities among zonal, meridional, and vertical winds inherent in a single radial velocity measurement. Receiving stations could include any combination of multiple spacecraft and an Earth station. Each station not aligned along the others' lines of sight yields an independent radial velocity vector. Three such vectors yield an unambiguous retrieval of three-dimensional winds.

6. CONCLUSION

There is much potential for future entry probe missions to achieve high-priority science objectives in the decades to come, and much potential for multinational collaborations in those missions. Recent NRC and NASA planning documents describe many high-priority atmospheric science objectives that cannot be achieved sufficiently well, or at all, by remote sensing techniques, and describe many mission concepts involving atmospheric entries, some specifically calling for entry probes. Other missions described in those documents could add entry probes to expand their science scope at a cost less than two separate missions. NASA has multiple programs in place for implementing such missions over a wide range of scales, from the relatively inexpensive Explorer class to the Flagship class, all open to international cooperation.

There is also much room for technological and methodological innovation in entry probes. Whether the innovations directly involve science investigations or are engineering improvements, the net result is to expand the envelope of science objectives entry probes can address. This can add to the list of potential future missions in which entry probes play a major role.

Any potential PI wanting to propose an entry probe mission must keep in mind that a vocal but small advocacy base generally does not result in implementation. Realizing missions requires significant (but fortunately, not unanimous) community consensus on mission objectives and their priorities.

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